# Summer Cloudtop Temperatures by NOAA Polar Orbiter AVHRR and Rawinsonde


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Points One through Four
(GARP, Temperature and Relative Humidity Profiles)

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## Introduction

Cloudtop temperature measurements by satellite have myriad uses in the scientific, business, and military fields today. The NOAA polar-orbiting satellite radiometer provides a compromise between improved resolution over the geostationary satellites and reduced timeliness of image collection. Channel four, from 10.3 to 11.3 micrometers (μm), gives a fair assessment of the temperature at the surface, or at the cloudtop where present. Establishing the accuracy of this measurement requires comparison against some ground-truth observation. This study compares the cloudtop temperature collected by in-situ rawinsonde during the OC3570 summer cruise of the second through the ninth of August, 2001 to those of NOAA satellites 14 and 16.

## Objective

The objectives of this experiment were to collect rawinsonde and satellite data, compare them, and analyze the results. Rawinsonde preparation, launch, and control console operations were needed to safely and effective get the information. Data handling and presentation skills would be put to the test. Knowledge of the satellite's characteristics and image correction were required. Along the way, increased proficiency using Matlab, Garp, XVU, and Teravision would be beneficial to future thesis research.

Another reason for choosing this particular experiment was to compare summer cloud profiles off the Monterey coast to winter profiles. As expected, LCDR Jim Rocha found multiple layers of cirrus around 6000 m and altocumulus around 3000 m during a previous winter cruise. The upper layers of thin, –30 $^{o}$C cirrus obscured the lower, -10 $^{o}$C cumulus. Together, the incoming scattered radiation at the sensor read much higher than expected, as if a single, warmer, therefore even lower, cloud had been present. Summer conditions of fog and stratus were expected to yield much better results.

## Pre-Cruise Planning

After the dates of the underway portion of the cruise were announced, the first step was to predict the satellite's orbital characteristics. We were told that balloon launches typically take place a little after dawn and before dusk, as well as required when interesting meteorological events arise. Due to the static nature of celestial orbits, overpass times are available months in advance. The R/V Big Sur would remain in the vicinity of Monterey Bay. Using a spatial limit of 500 miles nadir distance from Cypress Point at Pebble Beach avoided excess image stretch or the parallax error of clouds at increased altitude. A list of one or two most promising expected overpasses given to the watch teams refined intended launch times. Since all the overpasses are collected at the Naval Postgraduate School via HRPT receiver, these and any coincidental matches would be compared.

## Procedures

Several criteria must be met for the cloudtop temperature comparisons to be meaningful. Besides the spatial and temporal correlation, cloudy conditions must occur. The surface observation log provided a starting point for cloud coverage and wind information. Rawinsonde data provided the temperature, dewpoint temperature, humidity, and pressure information required to build temperature and relative humidity profiles. Cloudtop height was arbitrarily chosen to be at the steepest reduction in relative humidity over 95 %. Downcast data was preferred to upcast, as it reduced condensation collected on the humidity sensor and mixing to the rising balloon sphere.

Temperature at this three-dimensional position should match the brightness temperature radiance collected by the satellite from its altitude of 833 km. Ship position at balloon launch was known. Balloon travel due to winds, as well as image stretch would introduce error in latitude and longitude. Geonavigation is a term that explains image correction to remove the skew due to subtrack nadir distance from the balloon's position. The closest subtrack available was only 16 miles, and the farthest was 564 miles.

The AVHRR sensor's telescope mirror collects information in five channels at 40 kHz in a line of 2,048 boxes of 1.1 km each. A single swath width of 3,000 km or 55$^{o}$ to each side of its subtrack path is built as it spins at 360 revolutions per minute. An image grows as it passes downtrack, and it is overhead of its ground station for 16 minutes each orbit. Both POES orbit once every 102 minutes, or 14 orbits a day. They return overhead ascending from the equator each afternoon and descending from the pole in twelve hours, or on the second half of the seventh orbit later. Geonavigation removes precession effect as the earth rotates under the satellite, unlike GOES, which moves with the earth.

The visible wavelength radiance in channel one's bandwidth provided information about the synoptic conditions overhead during the cruise, while temperatures were inferred from the infrared wavelength brightness in channel four. The spectral response of channel four has its center at wavenumber 928 $cm^{-1}$, or 11 μm. Some energy from close frequencies would leak in, so Stefen-Boltzmann temperatures are clipped at

190 to 330 degrees Kelvin. With 10-bit processing, AVHRR can achieve resolutions of 0.12 K at minimal reduction due to radiance ignored in the sidebands outside the spectral response curve limits. This energy loss renders the estimated temperature slightly cooler than reality, but can be corrected within limits of the radiometer baseline. Also reducing radiance a 4-6 % absorption due to water vapor in the atmosphere and 1-2 % due to ozone. Changes due to atmospheric constituent fluctuations would be insignificant for this experiment.

Infrared radiation reaches the sensor from re-emission at the earth surface, passing through or scattering off a cloud or molecule, and re-emission by a molecule of aerosol or cloud water vapor. Optical thickness, or opacity, increases with cloud thickness. Reflectivity also increases as cloud particles freeze into ice crystals. The properties are important to satellite-derived cloud products discussed later.

**Post-Cruise Processing**

Building a table of balloon launch positions and times, overpass times and subtrack ranges, meteorological cloud cover, and wind speed provided the necessary filter of extraneous datasets. Of the 66 chosen overpasses, only 11 correlated with rawinsonde launches. Of these matches, only nine had clouds overhead and only five had working ".mat" Matlab-converted files. Thus, only four launch points remained, though another tethered-balloon profile comparison was attempted.

A FORETRAN code in XVU could have completed the Geonavigation, but manual corrections were made for the educational value of the process. Clear conditions over a spit of land near Crystal City, CA on the Oregon border verified the coastline and gridline fit of these efforts. Teravision provides a much simpler user interface and improved annotation and enhancement capabilities for the images than XVU.

Synoptic information added value to speculation of what was happened to the balloon once it entered the cloud layer and was lost from sight. Model data from COAMPS for 2-6 August and ETA for 6-9 August were rendered in GARP for each of the selected launches. Temperature and relative humidity profiles were produced in Matlab. Cloudtop temperatures were found at the height that relative humidity dropped quickest from above 95%. Dewpoint depression could also have been used. When temperatures deviated from AVHRR-derived brightness temperature, further information was collected. Entering the profile at the expected satellite-cloudtop temperature, moving back to the relative humidity curve, the second set of height and humidity values were collected. Future research may want to investigate this information. Generally, temperatures did not vary by more than half a degree or ten meters. A single cloud layer, total lack of upper cirrus, and care in rawinsonde sensor handling resulted in closely-matching cloudtop temperatures.

The first launch position was under a stratus blanket just outside Monterey Bay. Farther offshore, cloud street patterns can be seen in the visible image match stead flow with subsidence in GARP. Rawinsonde temperature, 12.40 $^{o}$C, was slightly less than AVHRR, 12.96 $^{o}$C. The preceding-mentioned method of height substitution lowered cloudtop level from 173 meters to a warmer 152 meters to match the radiometer. This launch suffered the greatest surface winds, 10 m/s, confirmed in the COAMPS run. Aloft, this balloon had the greatest trajectory, 20.76 km, and the greatest speed, 11.2 m/s. Inspection of the maximum velocity value 82.3 m/s shows that it is merely a surface spike. Integration of translation over time compared to LORAN downcast cloud position seemed beyond the scope of this particular study, though it might prove interesting. A GPS-equipped balloon would be more accurate for this endeavor. Also, GARP analysis comparing upper-level winds to higher trajectories seemed unnecessary, as the resolution of the IR sensor was large in comparison.

The second launch was delayed due to mechanical failure, but it passed through a steady band of stratus at 400-500 km and experienced the lightest winds observed. Temperature comparison was almost the closest, only 0.1 $^{o}$C different, and downstream trajectory distance was likewise the smallest. Relative humidity peaked at 92% on the upcast, but the “dry” 84% downcast profile structure looks consistent with a cloud band.

Launch number three was the closest in terms of subtrack error, only 15.9 km, and temperature, only 0.07 $^{o}$C apart. Although it had the greatest overpass delay, 41 minutes behind, synoptic conditions were the most steady, as seen on the attached figures. Convective stratocumulus can be seen building off Point Concepcion. Onshore, afternoon temperatures were the highest of the cruise, hitting 26.59 $^{o}$C in clear skies over Hurricane Point.

Matlab files were not produced for the balloons attached to the fishing pole. For the tethered balloon launched at 2135Z on 8 August, the temperature was higher than the others at 13.07$^{o}$C. An hour later, a balloon was released with temperature 12.3 $^{o}$C, and AVHRR had dropped to 12.05 $^{o}$C. Convective cells seem to bloom all over the visible image, and nearby values of 12.2 $^{o}$C to 12.5 $^{o}$C would provide a perfect match.

The final point considered in this study also had a tethered balloon. Though launched at 0049Z, eleven minute prior to overpass, the humidity sensor failed. A second launch was 41 minutes late, and a free launch was canceled. AVHRR cloudtop temperature over the ship was 11.87 $^{o}$C. Lower cloud heights are implied by shadows that can be discerned above the surface fog nearby. Channel four concurs with increased temperatures to the northeast of 12.5 $^{o}$C.

**Problems**

Comparing satellite values some angle away from nadir to the launch point of a balloon blown downstream introduces some error, which may be greater than the resolution of the radiometer instrument. However, the latitude and longitude error inherent to a Loran receiver may be greater than the trajectory distance. Further comparison would probably result in identical findings since a GPS receiver, more accurate then Loran, was used to determine launch position and the image geonavigation is assumed to be correct. Of course, that same GPS was used to initialize the Loran, so they will have identical launch position and electronic precision. This study simulates a Loran rawinsonde that doesn't change its position due to radio signals after launch. Further analysis could estimate AVHRR temperature at latitude and longitude of cloud entering the layer with GPS attached, or by applying the hypotenuse of integrated distance traveled ($\Delta$x, $\Delta$y) to launch position.

As stated earlier, 16 minutes elapsed while forming an AVHRR overpass image accrues some earth rotation, but when projected on a sphere, a slanted swath "banana peel" is displayed. Geonavigation corrects many forms of error: from precession, to parallax, to grid skew due to orbit deviation, to field of view image stretch (IFOV error, the tendency for round sightings to stretch into ovals away from nadir).

**Future Areas of Study (**Any of the following might be explored in subsequent cruises**):**

**Brightness Temperatures and Cloud Type Products**

Naval Research Laboratory uses cloudtop temperatures from GOES 4 km resolution channel four and heights from NOGAPS to determine likely cloud types. This product is used primarily for long-range aviation route planning during deep convection conditions. Model cloudtops below 15,000 feet are ignored, their warm temperatures relatively close to surface temperatures. NOAA-16 and beyond have an improved AVHRR with an added 1.6 μm channel for added discrimination capabilities between snow and ice, and winter or polar fog.

SCANDIA ’98 developed a more complex discrimination routine. It compares the difference in AVHRR channels one (visible) and two (near-infrared) to the difference in channels three (middle-IR) and four. As discussed previously, the first set yields likely cloud constitution based on reflectance, ice reflecting better than water. The second set brightness difference refines strato- and alto- layer clouds.

**Brightness Temperature and Fog Products**

Daytime fog and low stratus can match morning surface temperatures, deceptively vanishing as is burns off, revealed in the visible. At night, NRL has a routine that smoothes four adjacent resolution cells into a 4x4 km bin, then subtracts channel four (IR) from channel two (NIR). The radiance difference in the opaque clouds, at frequencies unable to seen by human eyes, reveals the clouds hidden below.

**Brightness Temperature and Ash Detection**

Volcanic ash can be detected during daylight hours by subtracting channel five from channel four.

## Conclusion

Amazingly, after a flight of over an hour and up to 20.76 km traveled, temperatures were within 0.5 $^{o}$C. Maximum trajectories were found at the first launch point. Offshore flow was nil; the balloon started up with a slight surface breeze from the north at 311$^{o}$, then the wind aloft reversed and the balloon passed overhead, returning only slightly just before splashing in the drink. Perhaps this can be attributed more to the continuous status found offshore of California in the summer more than the accuracy of the balloons. Fortunately, cloudtop temperature during this time of the year may be only slightly changed even 1,000 km away.

# PowerPoint Handout

Submitted separately.